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Is Systems Engineering Really Engineering?

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Is Systems Engineering Really Engineering?

- The question is rhetorical
- Of course, what I mean is "How do we ensure that systems engineering really is engineering?"
- To answer that, we first have to know what characterizes engineering
- It's too big a job to define engineering, but we can talk about some necessary conditions

What Do Engineers Do?

- **Engineers do two complementary things:**
  - they *describe* actual and imagined states of the world
    - actual states are facts
    - imagined states are designs and consequences
  - they *analyze* these descriptions
    - What are the consequences of a specified design?
    - What designs have a specified set of consequences?
- **Engineering analysis is distinguished by its reliance on science and mathematics to achieve rigor**
- **What is rigor?**
  - the quality or state of being very exact, careful, or strict
    - Merriam-Webster, 2017
  - scrupulous adherence to established standards for conduct of work
    - NASA Final Report of the Return to Flight Task Group, Appendix A.2, 2005

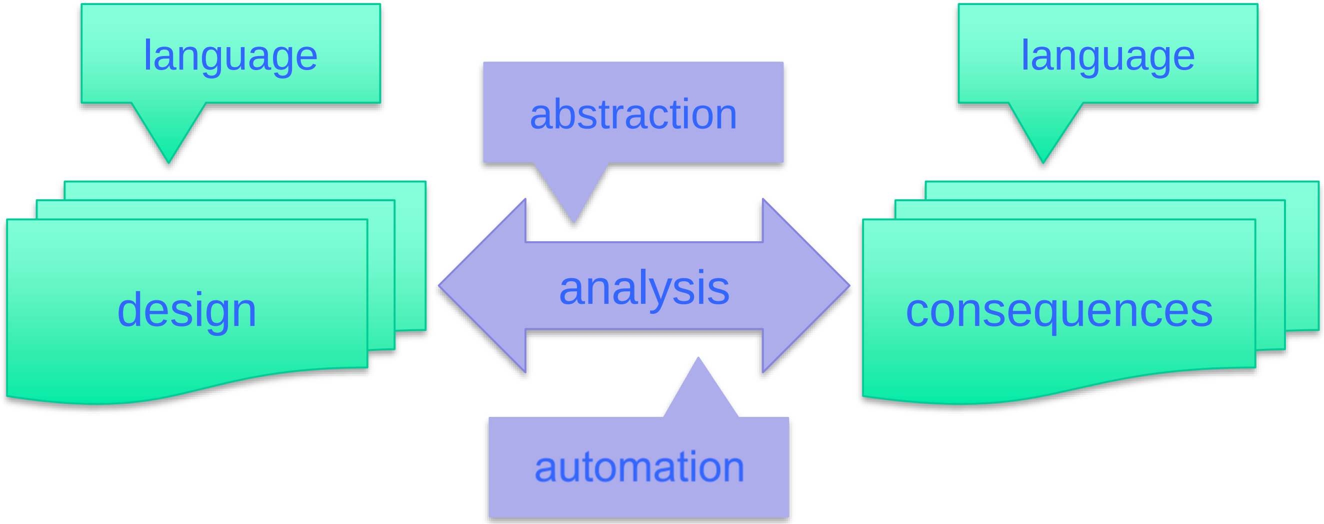
A Few Words About Rigor

- **Rigor in engineering is a distinguishing virtue**
  - it's what we do
- **Rigor requires no justification and we offer none**
- ***Rigorous* does not mean *detailed***
  - it means simplification must be justified
- **Rigor is not a value to be traded against time or money**
- **Rigor applies to all endeavors, simple and complex**
- **Rigor applies to all projects, large and small**
- **Rigor leads to**
  - better understanding of mission objectives and constraints
  - more precise descriptions of design concepts and realizations
  - more thorough and principled verification and validation
  - earlier and more effective remediation of defects
  - more accurate projections of budget and schedule

Where Do We Find Rigor?

- **Rigor in engineering manifests itself in three dimensions**
  - we use precise language to *describe* things
  - we use mathematical abstractions to *analyze* things
  - we use automation for both

- **Putting it together….**



Language

- **We can’t analyze what we can’t describe**
- **We can’t describe precisely without precise language**
- **Mature engineering disciplines define precise descriptive terms and taxonomic relationships**
  - e.g., resistor, capacitor, filter, amplifier, etc.
- **Mature engineering disciplines define composition rules that let us aggregate terms into “sentences” with clear meaning**
  - e.g., SPICE netlist circuit description
- **Precise languages generally manifest the following:**
  - vocabulary: terms
  - syntax: rules for constructing sentences
  - semantics: meaning in the real world
- **Real-world meaning in engineering comes from analysis**

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Abstraction

- **Abstractions are the key to analysis**
- **For example, an RC circuit can be modeled by a linear ordinary differential equation**
  - The equation is an abstraction in that it is a purely mathematical description of *idealized* behavior
  - We can perform operations on this abstraction; in fact we can *solve* it
  - The solution is a useful approximation of the *actual* behavior of the filter
- **Mathematical analysis is a hallmark of engineering**
  - Everything else is poetry or marketing or ….
- **The scope of applicable math has enlarged over time**
  - No longer just calculus, linear algebra and probability
  - Now formal logic, graph theory, abstract algebra, etc.
  - For example, telecom error-correcting codes employ algebra proudly claimed to be useless until the 20th century

Language and Abstraction

- **What is a capacitor?**
  - Is it necessarily a discrete component?
- **A better definition: something that exhibits *capacitance***
- **And what is capacitance?**
  - a specific analytical relationship between voltage and current: $I = C\, dV/dt$
- **Note the fundamental linkage of language to abstraction**
  - *capacitor* if and only if $I = C\, dV/dt$
- **This is true of engineering language in general**
  - What we say has *direct* analytical consequences
- **Abstractions shape language and vice-versa**
  - e.g., Modelica is a language of differential-algebraic equations

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Automation

- **Automation is critical for engineering because it preserves rigor: scrupulous adherence to the highest standards for the conduct of work**
  - Machines don't cut corners
- **Automation has its own abstractions (e.g., algorithms, data structures)**
- **These abstractions can be mapped to the abstractions of engineering analysis**
  - transitive closure maps to root cause analysis
- **Automation is fundamental to modern engineering because**
  - Well-designed languages are amenable to machine parsing
  - Many useful mathematical abstractions and related analyses are implemented in software libraries
  - Derivation of consequences of design can be automated
  - Design synthesis can be automated

What About Systems Engineering?

- **Systems engineers describe and analyze, but how well?**
- **Is Systems Engineering rigorous?**
- **Do we use precise language?**
- **Do we employ abstractions to empower analysis?**
- **Do we automate effectively?**
- **How can we do better?**

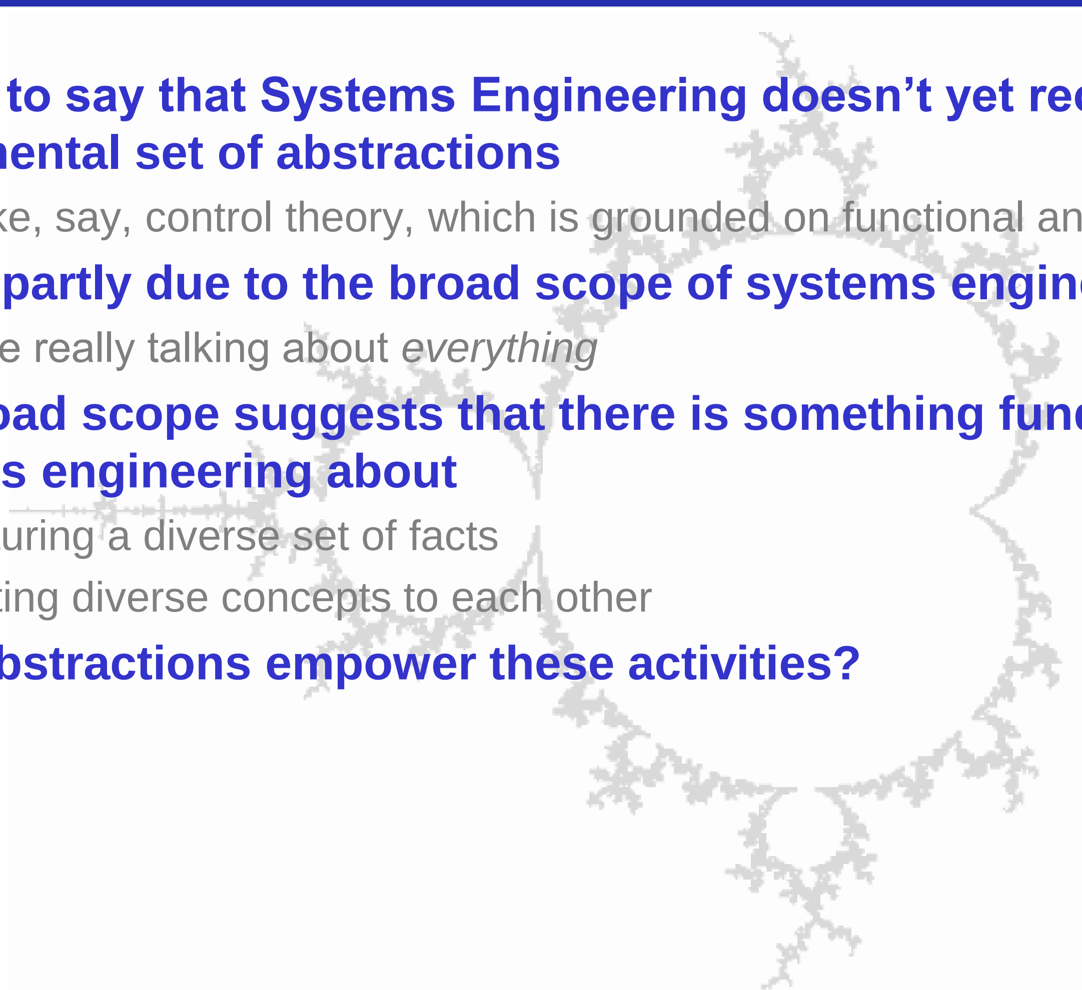
Systems Engineering Language

- **It's fair to say that Systems Engineering employs distinct concepts: *component*, *function*, *interface*, *requirement*, *risk*, etc.**
- **It's also fair to say that we use some words frequently without being very clear about meaning**
  - e.g., *system* vs. *subsystem*
- **As a discipline, we lack agreement on**
  - names for concepts
    - I call it *component*; what do you call it?
  - names for properties
    - How do we refer to an element's name? Its mass?
  - names for relationships
    - What's the relationship between a component and a function?
  - syntax for valid expressions composing concepts, properties, relationships
    - Can a function be performed by more than one component?

How Can We Do Better?

1. **First and foremost, recognize that there is well-established field of theory, practice, and technology dedicated to precise representation of knowledge**
   - called (obviously) *Knowledge Representation*
2. **Use the tools of Knowledge Representation and the Semantic Web to build communities of consensus around systems engineering language usage**
   - captured in formal ontologies
3. **Incorporate this consensus into, not just tools and software, but human language**
   - We should *talk to each other* using our language
4. **Incorporate this consensus into tools and software**
   - Particularly, SysML
5. **Reject ambiguity from our practices**
   - Being precise about uncertainty is good
   - Being ambiguous about anything is not

Systems Engineering Abstractions



- **It's fair to say that Systems Engineering doesn't yet recognize a fundamental set of abstractions**
  - unlike, say, control theory, which is grounded on functional analysis
- **This is partly due to the broad scope of systems engineering**
  - we're really talking about *everything*
- **The broad scope suggests that there is something fundamental to systems engineering about**
  - capturing a diverse set of facts
  - relating diverse concepts to each other
- **What abstractions empower these activities?**

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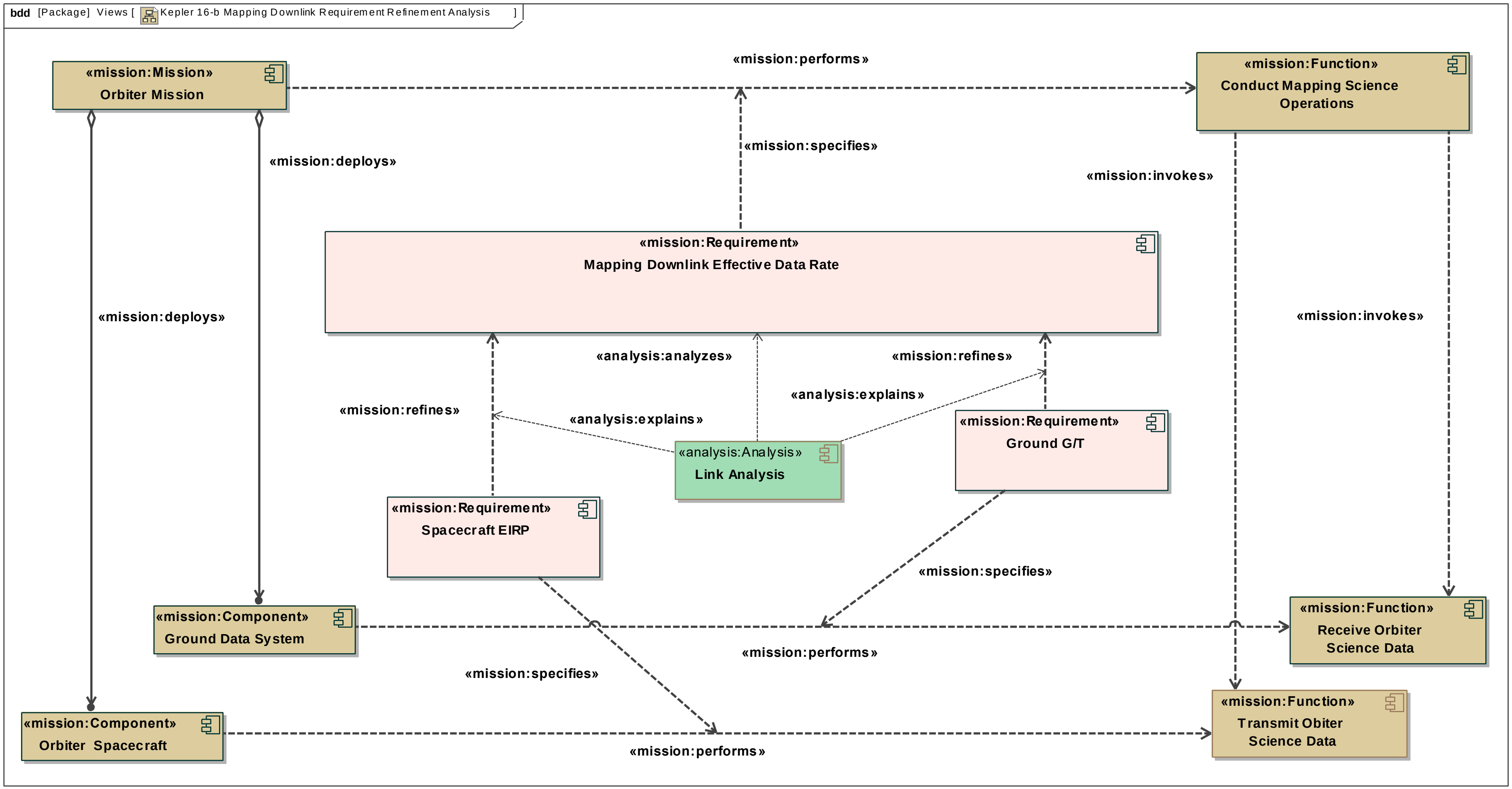
How Can We Do Better?

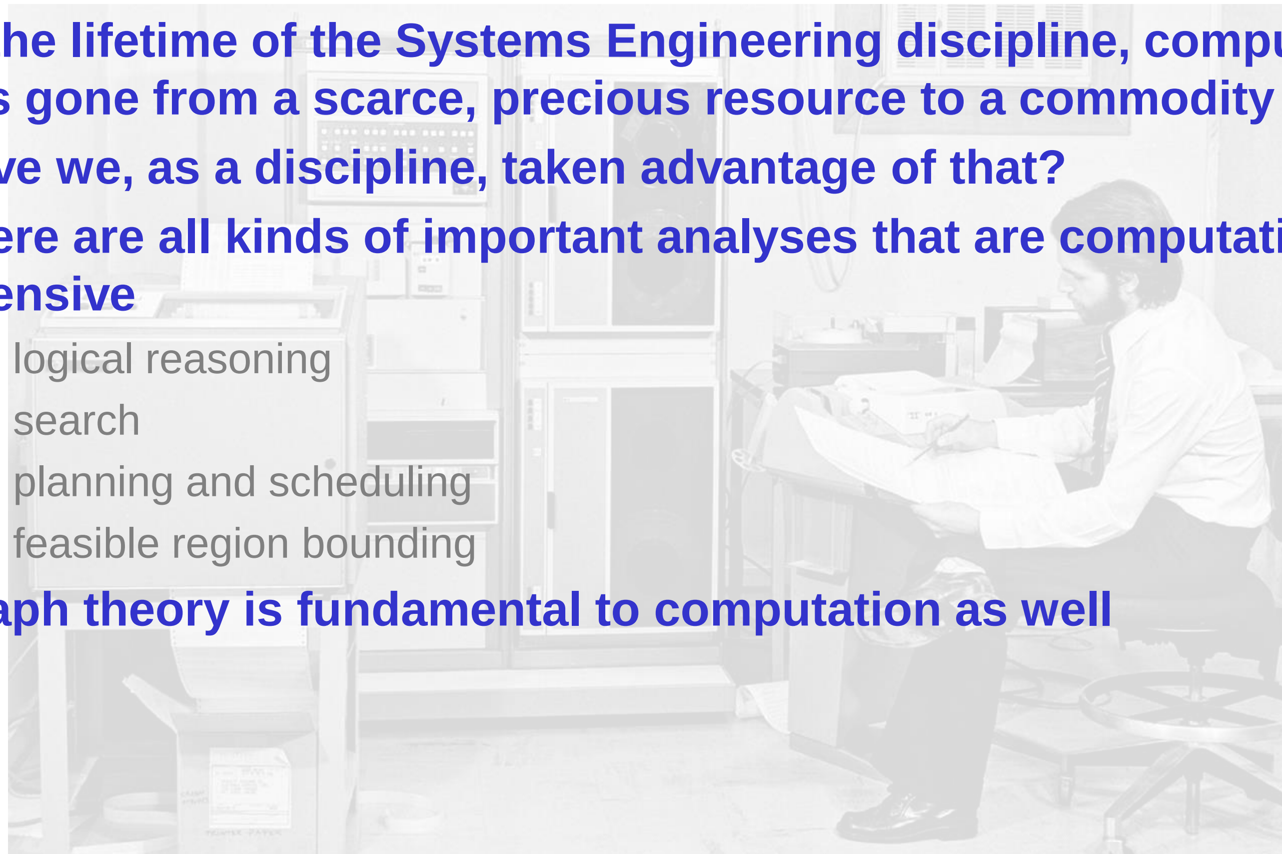
1. **Recognize that graph theory is the mathematical study of graphs, which represent pairwise relations between objects**
2. **Knowledge representation theory makes heavy use of graphs**
3. **We can use graph theory to structure and organize the facts (language assertions) about the objects of our design and analysis**
   - We can reason about whether the resulting graph is well-formed according to the rules of our language
   - We can reason about all kinds and degrees of relatedness
     - e.g., What requirements does this requirement directly refine?
     - Indirectly?
4. **Well-known graph algorithms have direct application**
   - connected components: fault propagation
   - transitive closure: state reachability
   - topological sort: root cause analysis

Example: Knowledge as a Graph



Systems Engineering Automation

- **In the lifetime of the Systems Engineering discipline, computing has gone from a scarce, precious resource to a commodity**
- **Have we, as a discipline, taken advantage of that?**
- **There are all kinds of important analyses that are computationally-intensive**
  - logical reasoning
  - search
  - planning and scheduling
  - feasible region bounding
- **Graph theory is fundamental to computation as well**



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Conclusion

- **Systems Engineering is really Engineering to the degree that it achieves rigor through in description and analysis through**
  - precise language with rules and meaning
  - mathematical abstractions
  - automation
- **Graph theory is a fundamentally applicable abstraction that empowers both description and analysis**
- **I don't like the term *Model-Based Systems Engineering* because it leads to silly questions like "What is a Model?"**
- **But I would *describe* MBSE as Systems Engineering practice that achieves rigor through use of**
  - **precise language for description**
  - **mathematical abstractions for analysis**
  - **effective automation**

Thank You

Questions?

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